

Quark and Gluon Degrees of Freedom in High-Energy Heavy Ion Collisions

Rainer J. Fries

*Cyclotron Institute, Texas A&M University, College Station, TX 77843
RIKEN/BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973*

Abstract

I discuss some recent progress in our understanding of high energy nuclear collisions. I will focus on two topics which I was lucky to co-pioneer in the recent past. One is recombination of quarks and its interpretation as a signal for deconfinement, the second is electromagnetic radiation from jets passing through a quark gluon plasma. This talk was given during the award ceremony for the 2007 IUPAP Young Scientist Award.

Key words: Relativistic Heavy Ion Collisions, Quantum Chromodynamics

PACS: 25.75.Dw, 24.85.+p

1. Introduction

Nuclear collisions at center of mass energies $\sqrt{s_{NN}} \gg 1$ GeV are carried out to look for new phases of quantum chromodynamics (QCD) in which quark and gluon degrees of freedom are explicit. A phase transition or rapid cross over into a deconfined quark gluon plasma (QGP) is found in lattice QCD calculations around $T_c \approx 180$ MeV and energy densities $\epsilon_c \approx 1$ GeV/fm³ [1]. At the highest available energies, achieved at the Relativistic Heavy Ion Collider (RHIC, $\sqrt{s_{NN}} = 200$ GeV), we have now convincing evidence that this new state of matter has been created [2]. This discovery has also come with many a surprise, e.g. strong indications from data that the matter at RHIC is far from an asymptotically free gas of quarks and gluons, but rather strongly coupled [3].

In these proceedings, I discuss two topics that emerged during the past couple of years after RHIC started running in the year 2000. The first one, recombination of quarks, was driven by experimental results which contradicted the way hadrons were expected

Email address: rjfries@comp.tamu.edu (Rainer J. Fries).

to be created in high energy collisions, through fragmentation from QCD jets. This was called the baryon puzzle or baryon anomaly in the early RHIC years. The solution is surprisingly straight forward and can be found in a simple recombination or coalescence picture which is valid in a phase space filled with partons. This was proposed around the same time in early 2003 by me and my collaborators at Duke University as well as by a few other groups. A completely satisfying dynamical description of this process is still lacking due to its non-perturbative nature, but a simple counting rule emerging from this picture has some very powerful implications as I will discuss below.

The second topic involves a new class of signals from the hot matter created in the collisions. It was long hoped that electromagnetic probes — photons and lepton pairs — can, due to their penetrating nature, shine light on the conditions inside the fireball and at early times during the collision. On the other hand, QCD jets are used as probes for the opacity and other transport properties of the medium. We proposed that the two can be combined in a novel way. Jets traveling through the QGP can produce real and virtual photons. We found that this process can contribute significantly to the total photon yield and that it can be used to learn about the medium. Unlike the case of quark recombination which grew out of an experimental puzzle and has since then been tremendously successful for the phenomenology at RHIC, the experimental sensitivity is not yet sufficient to routinely use photons from jets. This will change with the luminosity upgrade for RHIC which will permit the use of more exotic and extremely powerful probes.

2. Quark Recombination

We have learned in the past that hadrons produced with transverse momenta P_T of more than ~ 1 GeV/c come from QCD jets, originating from a single quark or gluon with large momentum p which fragments into a shower of hadrons. A given hadron has a fraction z of the original momentum, $P_T = zp$, $0 < z < 1$, and the probabilities for the fragmentation process are universal [4]. Among other things universality predicts a dominance of mesons over baryons. E.g. the ratio of protons over pions is expected to be

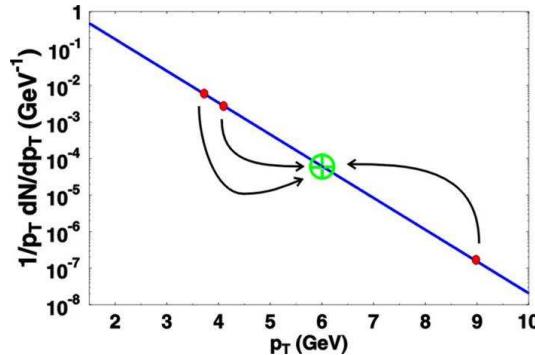


Fig. 1. Sketch of the fragmentation and recombination mechanism working on an exponential quark spectrum (black line). To create a 6 GeV meson (green dot), fragmentation needs to start from a quark or gluon with an average momentum of $\sim 9-12$ GeV/c, which is exponentially suppressed. Recombination uses two quarks with roughly 3 GeV/c which is much more likely.

roughly $0.2 \dots 0.3$. However, in nuclear collisions at RHIC a ratio of $p/\pi \approx 1$ was found for $P_T \approx 4 \text{ GeV}/c$, well in the range where fragmentation was expected to work [5].

The solution of this puzzle can be found by realizing that fragmentation necessitates the absence of any other partons which might interact with the jet. This puts tight limits on the applicability of the fragmentation picture to nuclear collisions with thousands of particles created. Rather, with phase space filled with partons in a thermalized medium, hadron production should proceed through recombination or coalescence of quarks into the valence structure of hadrons [6,7,8,9,10]. Most implementations of the recombination process use an instant projection of quark states onto hadron states utilizing the wave function ψ of the baryon or meson and assuming thermal distribution functions f for quarks. E.g. for pions one has

$$\frac{dN_\pi^+}{d^3P} = C_{\pi^+} \int d\Sigma \int \frac{d^3q}{(2\pi)^3} f_u(P/2 - q) f_{\bar{d}}(P/2 + q) |\psi(q)|^2 \quad (1)$$

where Σ is the hypersurface of hadronization and C_{π^+} is a combinatorial factor [7]. This ansatz preserves 3-momentum, but not energy, and it is hence only valid for not too small momenta P_T .

For thermal quark distributions $f \sim e^{-p/T}$ there is no suppression of baryon production compared to mesons, leading naturally to baryon/meson ratios of order unity. On

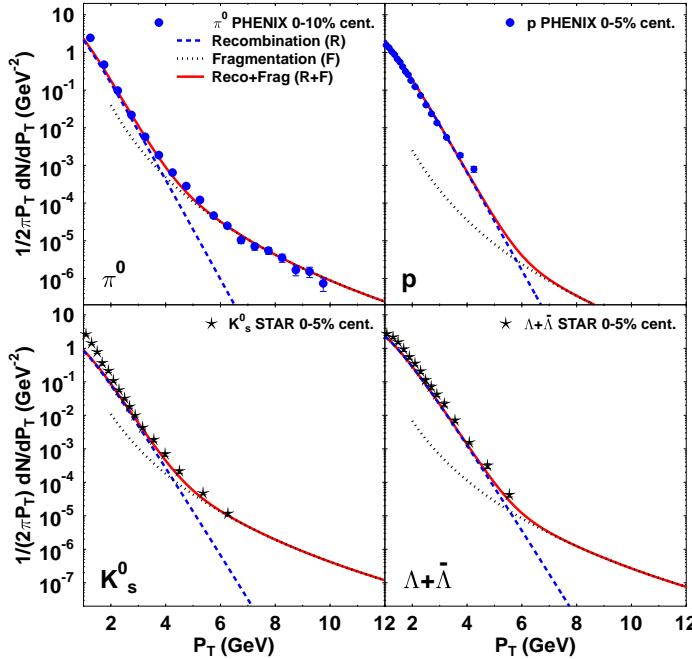


Fig. 2. Spectra for pions, protons, kaons and Lambdas in a combined recombination and fragmentation approach [7] compared to data from RHIC. Shown are the fragmentation contribution (dotted line), recombination from the thermal medium with temperature T_c (dashed line) and the sum of both contributions. The different transition regions for mesons and baryons are clearly visible.

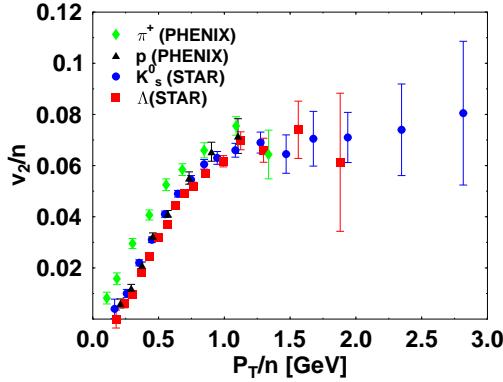


Fig. 3. Measured elliptic flow v_2 for different hadron species at RHIC as a function of P_T . The different data sets collapse onto a single line if both axes are scaled by the number of valence quarks for each hadron species. Small deviations from universality can be explained in a scaling model using transverse kinetic energy instead of P_T .

the other hand, one can show that recombination on thermal spectra is always more efficient than fragmentation, as indicated in Fig. 1. Fig. 2 shows a typical result for P_T spectra of several hadron species compared with experimental data from RHIC (see [7] for details). The transition from the recombination dominated domain to the fragmentation dominated region occurs around $P_T \approx 4 \text{ GeV}/c$ for mesons. For baryons the transition is shifted to about $6 \text{ GeV}/c$ due to the inefficiency of the fragmentation process for baryons. Below $P_T \approx 1.5 \text{ GeV}/c$ the simple projection formula loses its validity.

Recombination has a very intriguing consequence for elliptic flow v_2 . Elliptic flow arises from the ellipsoidal shape of the overlap zone of the two nuclei for finite impact parameters $b > 0$. In those cases there is no spherical symmetry in the transverse plane. As a result the pressure gradients along the smaller and larger transverse radii of the fireball are different and lead to a larger boost of particles in the direction where the fireball was originally thinner. The final particle spectra can be analyzed in a harmonic series in the azimuthal angle ϕ

$$1 + 2v_2 \cos 2\phi + \dots \quad (2)$$

Suppose elliptic flow is born in a partonic phase, and the value for quarks just before hadronization is $v_2^p(P_T)$. Recombination then predicts the value of v_2 for all hadron species just after hadronization. Just using the simplest assumptions about the recombination process this leads to a universal scaling law

$$v_2^h(P_T) = nv_2^p(P_T/n) \quad (3)$$

where h is any hadron and n is its number of valence quarks [7,9,11]. Hence recombination predicts that the elliptic flow for all meson species is the same, and that the same is true for all baryons. Moreover it predicts that baryons and mesons are related by a simple scaling of both v_2 and P_T by 3 and 2 respectively. This is impressively confirmed by experimental data [12,13] as shown in Fig. 3 where v_2 for different hadrons are plotted on scaled axes. All data points fall on one universal curve which indicate the quark v_2 . The scaling is even more impressive if the transverse kinetic energy is used instead of P_T , an

indication for the hydrodynamic origin of flow (see [14] for a recent attempt to explain kinetic energy scaling).

There are many caveats to this simple picture, some of which have been successfully overcome, while others are still puzzling. As an example for the former, let me mention 2-particle correlations [15,16] which first seemed to be incompatible with recombination, but have now been implemented in a fashion compatible with data [17,18]. On the other hand a persisting problem is the fact that recombination models are very sensitive to space-momentum correlations in the quark phase and in connection with data give tight constraints, in contradiction to other models [19].

Nevertheless, recombination is an extremely successful model for hadron production at intermediate P_T in high energy nuclear collisions. It also leads to some more general insight. The scaling law in particular makes the quark degrees of freedom in hadrons explicit. However, unlike quark counting rules in elementary processes, the observable v_2 describes the effect of matter moving collectively. The collectivity together with the scaling law leaves no doubt that the hydrodynamic expansion of the system starts in a phase which is partonic, not hadronic. Therefore, the scaling law for v_2 might be the best *direct* signal for deconfinement available at this moment.

3. Photons from Jets

Let us now discuss jets and electromagnetic signals from their interaction with quark gluon plasma. Photons and dileptons (from virtual photons) have long been considered as unique probes of dense nuclear matter, since their mean free path exceeds by far the size of a nucleus. Therefore, photons even when emitted deep inside the fireball or very early during the collision will reach the detectors unaltered. Thermal radiation of photons and dileptons is supposed to be the ideal thermometer for the plasma. However, in the history of heavy ion collisions, electromagnetic probes have always been a challenge for experimentalists, requiring large numbers of events and mature analysis tools. E.g. the background from π^0 decays is very problematic for the extraction of direct photons.

Even after subtracting decay photons, there are several sources of direct photons besides the thermal radiation, as indicated in Fig. 4. Prompt photons from initial hard scatterings and bremsstrahlung from jets are present in elementary proton-proton collisions as well as nuclear collisions. Thermal radiation appears in nuclear collisions, both from a hot hadronic medium and from a QGP. P_T as a variable helps to distinguish the different sources, with the exponential thermal spectrum being most prominent below 1 GeV/c, and with bremsstrahlung and direct hard photons becoming dominant at large

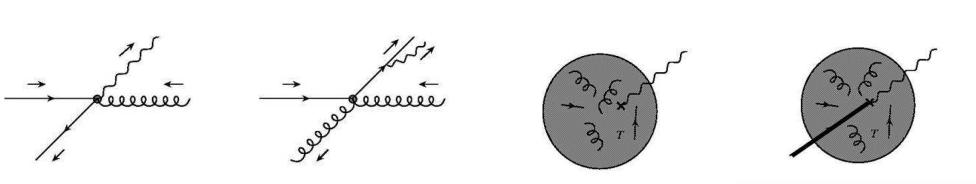


Fig. 4. Different contributions to direct photon production in heavy ion collisions. From left: prompt photons from initial hard scatterings of partons; (vacuum) bremsstrahlung from jets; thermal photons from the quark gluon plasma; jets emitted from jet-plasma interactions

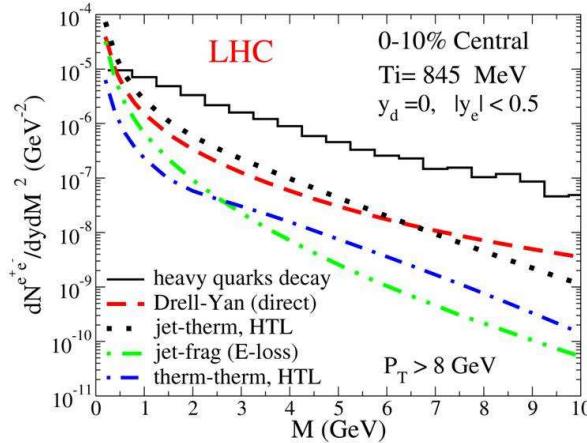


Fig. 5. Yield for electron-positron pairs from different sources at the LHC [25]. The sources are thermal radiation (dash-dotted line), direct primary hard scattering (dashed line), bremsstrahlung (dash-dot-dotted line) and jet-medium interactions (dotted line). The background from correlated charm and bottom decays is shown as well. Even for relatively large $P_T > 8$ GeV/c jet-medium dileptons are still the dominant source at intermediate masses.

P_T .

In 2002, we suggested that jets traveling through the plasma can radiate photons (and dileptons) as well and that this might be an important process [20,21]. The leading order channels for real photons are annihilation, q (jet) + \bar{q} (medium) $\rightarrow \gamma + g$ and Compton scattering q (jet) + g (medium) $\rightarrow \gamma + q$. These processes creating photon radiation come about naturally once the presence of gluon radiation (involved in the energy loss of jets [22]) has been established. Since the corresponding cross sections are strongly forward and backward peaked, the resulting photon spectra are directly proportional to the input jet spectra. Therefore, the term jet-photon conversion was coined for these processes.

Initially we found that the brightness of this new source is comparable to the other sources at intermediate P_T of a few GeV/c. Refined calculations, also taking into account energy loss of the jet before the photon is produced, confirm this result [23,24,25]. Fig. 5 shows a recent calculation for expected dilepton yields at the Large Hadron Collider (LHC, $\sqrt{s_{NN}} = 5.5$ TeV) as a function of dilepton mass M [25]. At LHC the relative contribution from jet-medium photons will be even larger than at RHIC.

Why should one be excited about this new source of photons? Obviously it is important to know all contributions. But there is more, jet-medium photons are sensitive to the temperature, similar to thermal radiation, and can be used as a second, independent constraint on the temperature evolution of the fireball. Moreover, they can be measured at a P_T of several GeV/c where the π^0 background is suppressed by a factor of 5 due to jet quenching [22], a luxury which is not happening at small P_T .

They are also sensitive to jet energy loss. However, they probe jet path integrals different from those which determine hadron observables. The latter probe the propagation of a jet to the space-time boundary of the fireball, while the former only probe up to the point of photon production. Thus jet-medium photons also encode information about energy loss which is complementary to that contained in hadronic observables.

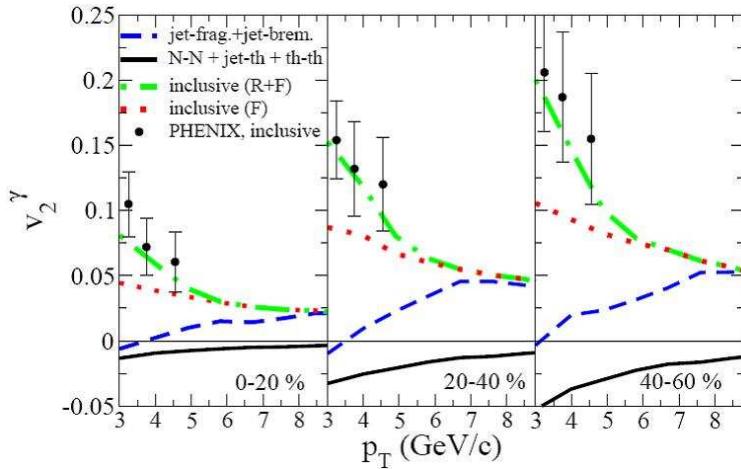


Fig. 6. Elliptic flow of photons from different sources for three different centralities as a function of photon P_T [26]. The result for primary hard photons, thermal photons and jet-medium photons (solid line) and bremsstrahlung photons (dashed line) are shown separately. [Bremsstrahlung photons here also include medium-induced bremsstrahlung (besides the vacuum part) which is not discussed in detail in the text. Medium-induced bremsstrahlung can also lead to negative v_2 .] The reason to show both results is the hope that both contributions might in the future be separable by isolation cuts. The effect of negative v_2 is clearly visible and can be as large as -5% . The dotted line shows the expected v_2 of all photons including decays of pions from fragmentation, the dashed line also includes decays of pions from recombination. Data from PHENIX is for inclusive photons without background subtraction.

All of this is very difficult to extract from single inclusive measurement, e.g. the photon spectrum as a function of P_T . In fact, although the photon spectra measured at RHIC can be nicely described by calculations including jet-medium photons, parameter space is flexible enough to allow for fits of the data excluding jet-medium interactions. To resolve this issue one has to go to less inclusive measurements and to correlations. Therefore, we recently suggested photon elliptic flow as an interesting observable [26]. Photons from thermal emission and photons from vacuum bremsstrahlung (which experience energy loss) have elliptic flow $v_2 > 0$, i.e. in phase with the v_2 of hadrons. There are more photons from these sources in the direction where the fireball was originally thinner. However, the opposite is true for jet-medium photons. The thicker the medium, the more likely it is that the jet is converted to a photon (remember that this is a rare process). Thus the v_2 for jet-medium photons should be negative, providing an additional possibility to distinguish it from other sources.

Fig. 6 shows the result of a recent calculation of photon elliptic flow from [26]. The expected v_2 of direct photons is numerically small and can reach negative values at intermediate P_T . The data shown still contains the background from π^0 and η decays. First attempts by PHENIX to extract the v_2 of direct photons yielded results which are compatible with zero with rather large error bars [27]. Future analyses will improve these results and give a definite answer about the importance of jet-medium photons and dileptons. Even more promising, but even harder to extract experimentally are jet-photon and hadron-photon correlations. Such challenging but powerful measurements will make jet-medium photons an important topic for future runs at RHIC and LHC.

4. Conclusions

I am particularly grateful to all my collaborators on these projects, Steffen A. Bass, Charles Gale, Berndt Müller, Chiho Nonaka, Dinesh K. Srivastava and Simon Turbide. I wish to thank the IUPAP C-12 committee for the honor to be a recipient of the IUPAP Young Scientist Award and the organizers of INPC 2007 for a wonderful conference experience. This work is supported by DOE grant DE-AC02-98CH10886, the RIKEN/BNL Research Center and the Texas A&M College of Science.

References

- [1] F. Karsch, Nucl. Phys. A **698**, 199 (2002);
M. Cheng *et al.*, Phys. Rev. D **74**, 054507 (2006).
- [2] J. Adams *et al.* (STAR Collaboration), Nucl. Phys. A **757**, 102 (2005);
K. Adcox *et al.* (PHENIX Collaboration), Nucl. Phys. A **757**, 184 (2005).
- [3] M. Gyulassy and L. McLerran, Nucl. Phys. A **750**, 30 (2005).
- [4] J. C. Collins and D. E. Soper, Nucl. Phys. B **194**, 445 (1982).
- [5] B. I. Abelev *et al.* (STAR Collaboration), Phys. Rev. Lett. **97**, 152301 (2006).
- [6] R. J. Fries, B. Müller, C. Nonaka and S. A. Bass, Phys. Rev. Lett. **90**, 202303 (2003);
R. J. Fries, B. Müller, C. Nonaka and S. A. Bass, J. Phys. G **30**, 223 (2003).
- [7] R. J. Fries, B. Müller, C. Nonaka and S. A. Bass, Phys. Rev. C **68**, 044902 (2003).
- [8] R. J. Fries, J. Phys. G **30**, 853 (2004).
- [9] V. Greco, C. M. Ko and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003);
V. Greco, C. M. Ko and P. Levai, Phys. Rev. C **68**, 034904 (2003).
- [10] R. C. Hwa and C. B. Yang, Phys. Rev. C **67**, 034902 (2003);
R. C. Hwa and C. B. Yang, Phys. Rev. C **67**, 064902 (2003).
- [11] S. A. Voloshin, Nucl. Phys. A **715**, 379 (2003);
Z. W. Lin and C. M. Ko, Phys. Rev. Lett. **89**, 202302 (2002);
D. Molnar and S. A. Voloshin, Phys. Rev. Lett. **91**, 092301 (2003).
- [12] J. Adams *et al.* (STAR Collaboration), Phys. Rev. Lett. **92**, 052302 (2004).
- [13] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **91**, 182301 (2003).
- [14] L. Ravagli and R. Rapp, arXiv:0705.0021 [hep-ph].
- [15] C. Adler *et al.* (STAR Collaboration), Phys. Rev. Lett. **90**, 082302 (2003).
- [16] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. C **71**, 051902 (2005);
A. Sickles (PHENIX Collaboration), J. Phys. G **30**, 1291 (2004).
- [17] R. J. Fries, S. A. Bass and B. Müller, Phys. Rev. Lett. **94**, 122301 (2005).
- [18] R. J. Fries, Phys. Conf. Ser. **27**, 70 (2005);
S. A. Bass, R. J. Fries and B. Müller, Nucl. Phys. A **774**, 635 (2006).
- [19] S. Pratt and S. Pal, Nucl. Phys. A **749**, 268 (2005).
- [20] R. J. Fries, B. Müller and D. K. Srivastava, Phys. Rev. Lett. **90**, 132301 (2003);
D. K. Srivastava, C. Gale and R. J. Fries, Phys. Rev. C **67**, 034903 (2003).
- [21] C. Gale, T. C. Awes, R. J. Fries and D. K. Srivastava, J. Phys. G **30**, S1013 (2004).
- [22] S. S. Adler *et al.* (PHENIX Collaboration), Phys. Rev. Lett. **91** (2003) 072301.
- [23] R. J. Fries, B. Müller and D. K. Srivastava, Phys. Rev. C **72**, 041902 (2005).
- [24] S. Turbide, C. Gale, S. Jeon and G. D. Moore, Phys. Rev. C **72**, 014906 (2005).
- [25] S. Turbide, C. Gale, D. K. Srivastava and R. J. Fries, Phys. Rev. C **74**, 014903 (2006).
- [26] S. Turbide, C. Gale and R. J. Fries, Phys. Rev. Lett. **96**, 032303 (2006).
- [27] S. S. Adler *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **96**, 032302 (2006)